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Effects of Core Type, Placement, and Width, on the Estimated Interstrand Coupling Properties of QXF-Type Nb_3Sn Rutherford Cables

E. W. Collings, M. D. Sumption, M. Majoros, X. Wang, and D. R. Dietderich

***Abstract*— The coupling magnetization of a Rutherford cable is inversely proportional to an effective interstrand contact resistance, R_{eff}, a function of the crossing-strand resistance, R_c, and the adjacent strand resistance, R_a. In cored cables R_{eff} varies continuously with *W*, the core width expressed as percent interstrand cover. For a series of un-heat-treated stabrite-coated NbTi LHC-inner cables with stainless-steel (SS, insulating) cores $R_{eff}(W)$ decreased smoothly as *W* decreased from 100% while for a set of research-wound SS-cored Nb_3Sn cables R_{eff} plummeted abruptly and remained low over most of the range. The difference is due to the controlling influence of R_c – 2.5 μΩ for the stabrite/NbTi and 0.26 μΩ for the Nb_3Sn. The experimental behavior was replicated in the $R_{eff}(W)$s calculated by the program CUDI© which (using the basic parameters of the QXF cable) went on to show in terms of decreasing *W* that: (i) in QXF-type Nb_3Sn cables (R_c = 0.26 μΩ) R_{eff} dropped even more suddenly when the SS core, instead of being centered, was offset to one edge of the cable, (ii) R_{eff} decreased more gradually in cables with higher R_cs, (iii) a suitable R_{eff} for a Nb_3Sn cable can be achieved by inserting a suitably resistive core rather than an insulating (SS) one.**

***Index Terms*—Core, Magnetization, Nb_3Sn, Rutherford Cable**

I. Introduction

IN THE LHC colliding synchrotron, between proton injection at 0.535 T and beam accumulation at 8.33 T the current is ramped at 10 A/s corresponding to a dipole-field ramp rate of about 7.5 mT/s. This time-varying field to which the magnets' Rutherford cables are exposed induces interstrand coupling currents (ISCCs) that circulate around paths created: (i) by the connecting of upper and lower sections of strand by crossover points of contact each of resistance R_c and (ii) by the side-by-side contact between adjacent strands characterized by a cable-edge to cable-edge resistance R_a. The magnetization associated with these coupling currents, M_{coup}, induces multipolar harmonics in the dipolar or quadrupolar bore field. Field ramping also generates "supercurrents" [1] or boundary-induced coupling currents (BICCs) [2, pp.101-141][3][4] that flow over the whole cable length and also induce field errors. The field distortions produced by ISCCs and BICCs [5] can be suppressed by making Interstrand Contact Resistance, ICR, sufficiently high; but still low enough to ensure current sharing between strands and hence stability [6]. For LHC cables, the subject of many studies, it has been agreed that R_c should be in the range 15 ± 5 μΩ [5] or 20 ± 10 μΩ [7] and (ii) that R_a can be very much smaller but typically not less than 0.2 μΩ [2]

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II. Background

A. Coupling Magnetization

Based on an expression due to Sytnikov et al [8] for coupling loss in a Rutherford cable due to a time-varying field, *dB/dt*, the magnetization due to coupling currents, M_{coup}, can be extracted from $Q_{coup}= 4M_{coup}B_m$, and is given (SI units) by

$$M_{coup} = \left(\frac{1}{3}\right)\left(\frac{w}{t}\right)L_p\left(\frac{N^2}{20}\right)\left[\frac{1}{R_c}+\frac{20}{N^3R_a}\right]\left(\frac{dB}{dt}\right). \qquad (1)$$

Here *w/t* is the width/thickness ratio of an *N*-strand cable, L_p is one-half of the transposition pitch, and the applied field has an amplitude B_m directed normal to the cable's flat face (the face-on or FO orientation).

Equation (1) expresses the FO coupling magnetization in terms of a pair of parallel resistors R_c and $(N^3/20)R_a$ enabling an "equivalent" or "effective" R_{eff}, defined as $1/R_{eff} = 1/R_c + 20/N^3R_a$, to be introduced into (1), leading to

$$M_{coup} = \left(\frac{1}{3}\right)\left(\frac{w}{t}\right)L_p\left(\frac{N^2}{20}\right)\left[\frac{1}{R_{eff}}\right]\left(\frac{dB}{dt}\right). \qquad (2)$$

Although R_{eff} itself is not part of the resistive-network model of the cable, regarded just as a number it is a useful index of coupling magnetization. For a 28-strand LHC-inner cable with "standard" ICRs, R_c = 20 μΩ and R_a = 0.2 μΩ the parallel-resistor model depicts the 20 μΩ R_c shunted by $(N^3/20)$*0.2 μΩ = 220 μΩ, which does little to suppress the combined $R_{eff} \approx R_c$. The R_{eff} index is especially useful when cores of varying widths are introduced in which case R_{eff} would increase from ≈ 20 μΩ to 220 μΩ as the core coverage, *W*, increased from 0 to 100%.

B. ICR Measurement in Rutherford Cables

The ICR in cables (combinations of R_c and R_a in the case of Rutherford cables) can be measured by a direct current-voltage (*I*-*V*) method. In this method one end of the cable is bared and current leads are attached to strands 1 and *N*/2+1; voltage is measured between strand 1 and all the others in succession [2, p.93][7][9][10]. Based on the Sytnikov equations, an R_{eff} can also be obtained from the frequency dependence of total AC loss measured using He-boil-off calorimetry [2, p.95] and/or pickup-coil magnetometry [9]. The Nb_3Sn "research cables" referred to here were wound at the Lawrence Berkeley National Laboratory (LBNL) and the Fermi National Accelerator Laboratory (FNAL), with strand counts of 27 to 35 and with widths of 10 to 15 mm. Stacks of 40 cm long cable segments were prepared for measurement following a simulation of magnet construction procedures: mounted in fixtures designed to apply side-constraint, the stacks were uniaxially compressed to 20 MPa, reaction-heat treated (RHT) for typically 72h/210ºC + 48h/400ºC + 48h/650ºC, placed in molds, re-compressed to 5 MPa, and vacuum impregnated with CTD-101 resin.

For comparison with cable results, ICR values can also be derived from field-advance, multipole, and AC-loss measurements on accelerator magnets, see below.

III. ICR Control in Rutherford Cables

Over the years many approaches to optimizing ICR in NbTi cables have been taken. ICR increases have been achieved: (i) by applying metallic or insulating coatings to the individual strands and (ii) by inserting insulating or metallic ribbons between the two layers of the cable. But whatever technique is used it is known that the ICR is controlled by the resistance of a surface oxide layer [11]. For the LHC cables a special Cu-diffusion-produced oxide layer was intended to provide the desired 20 μΩ ICR between stabrite-coated NbTi/Cu strands after heat treatment (HT) in dry air. Before HT the R_c of the coated strand is only a few μΩ; during HT as R_c increases so also does R_a which would best remain small. The more desirable "anisotropic ICR" can be achieved by the introduction of a thin stainless steel (SS) core [12][13]. In fact the R_{eff} of a non-HT stabrite-coated cable was found empirically to increase exponentially with *W* [13] according to a fitted $R_{eff} = 3.15 + 0.363*\exp(0.059*W)$, Fig. 1. The fitted R_{eff} of 136 μΩ at W = 100% indicates an R_a of 0.16 μΩ.

A. ICR in NbTi-Wound Dipoles and Quadrupoles

Coupling currents generating by the ramping-up of current in LHC dipoles and quadrupoles produce small increases, B_1 and B_2 (~0.05 mT), in the main fields, B_0. Normalized to B_0 these increases ("field advances", FA) are represented by the "units" b_1 and b_2, 1 unit being equal to 10^{-4}. The field advances are accompanied by normal- and skew harmonics represented by b_n and a_n (generally c_n, and 2*n* equals the pole number). ICR values have been obtained from measurements

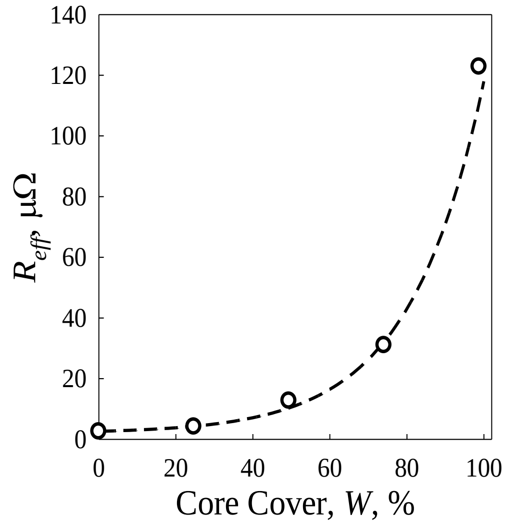

Fig. 1. R_{eff} versus W for SS-cored stabrite-coated non-HT Rutherford cables [11][12].

at CERN of FA, c_n, and energy (AC) loss in current-ramped LHC dipoles and quadrupoles [14][15][16].

For six "pre-series" LHC dipoles [15] the values of R_c obtained from AC loss measurement during current ramping at 10 A/s were 30, 60, 70, >100, and >100 μΩ, much larger than the production target of 15 μΩ. Accordingly the 10 A/s b_3, for example, at the injection field of 0.54 T was only 0.053 units compared to an expected 0.46. Likewise high values of R_c have been obtained in measurements of LHC quadrupoles [16].

Field Advance: Measurements of FA (for both apertures) were performed on a string of eight main quadrupoles at current ramp rates of 10-50 A/s [16]. The average FA was 1.0-2.4 units, much smaller than the 15 units associated with the target quadrupole R_c of 20 μΩ. In fact the FA versus *dI/dt*-calculated values of R_c were in the range of 95-230 μΩ.

Multipoles: Rotating-coil measurements of multipole amplitudes were made on seven main quadrupoles (both apertures) [16]. The average value of b_3 (reference radius 17 mm, *I* = 760 A, *dI/dt* = 10 A/s) was 0.206 units and the deduced average R_c was 135 μΩ.

AC Energy Loss: Current-voltage measurements of energy loss versus *dI/dt* performed on three LHC quadrupoles (both apertures) enabled R_c values of 159, 169, 171, 173, 181, and 198 μΩ to be obtained. The dipole- and quadrupole-measured values of R_c can be compared with those measured on relevant cable samples. As reported in [16] the average cable-measured values were 194±73 μΩ (before curing) and 66±40 μΩ after 30min/190ºC curing.

B. ICR of Accelerator Cables in General

As summarized in [14] the current ramping of LHC magnets produces field errors: (i) in dipoles of about 1 unit of b_1 and less than 0.1 units of c_n, consistent with R_c well above 50 μΩ, (ii) in quadrupoles of about 2 units of b_1 and less than 0.2 units of c_n, consistent with R_c between 100 - 150 μΩ [14].

Evidently such ICRs have contributed to the successful operation of the LHC dipoles and quadrupoles to date and hence could be recommended as new target values. But when translating these results to future cables it must also be recognized that the true coupling-induced factor determining field error is the coupling magnetization, M_{coup}. Equation (2) shows that M_{coup} is not only proportional to $1/R_{eff}$ (i.e. $1/R_c$) and dB/dt, but also the cable-design parameters (w/t), L_p, and particularly N^2. So to keep M_{coup} constant from cable-to-cable the "target R_c" must be suitably modified. While no target is as of yet specified, we can consider, for example, if R_{eff} = 125 μΩ is picked for an LHC-inner type cable with (w/t), L_p, and N values of 7.94, 55 mm, and 28, then for an un-cored "QXF-type" cable with its corresponding cable-design parameters of 10.1, 54.5 mm, and 40, R_{eff} would need to be multiplied by 2.6. This is where the advantage of a core is felt. Although for an uncored cable (1) shows that M_{coup} is proportional to $(N^2/20)/R_c$, for a full-insulating-core cable it is proportional to $1/NR_a$ (this can be seen by letting $R_c \rightarrow\infty$ in (1)); so not only is M_{coup} decreased, but it decreases further with increasing N.

IV. ICR in Nb_3Sn Rutherford Cables

A. Uncored Nb_3Sn Cables

Over the years, the calorimetrically and magnetically measured R_{eff} (i.e. R_c) values we have obtained for uncored Nb_3Sn cables have been: 0.24 [9], <0.1 [17], 0.17, 0.37, 0.39 [18], 0.24 [19], 0.37 [20], 0.23 [21], 0.15, 0.36 [22], 0.4 [23], 0.37 [24], 0.22 [25], 0.10, 0.17. 0.25 [26], 0.33 [27] for an average of 0.26 ± 0.1 μΩ along with two "high" values of 1.76 [22] and 1.93 [18]. The sintering together of the Cu surfaces of the Nb_3Sn/Cu strands during RHT under pressure is responsible for the very low R_c; clearly a core is needed to separate the Cu/Cu interfaces.

B. Stainless-Steel-Cored Nb_3Sn Cables

In a search for the optimal core width an assortment of research cables of various sizes, furnished with 25 μm stainless-steel (SS) cores of various widths, were wound at LBNL and FNAL. Table I lists the calorimetrically and magnetically measured results in ascending order of R_{eff}, the quantity W representing the extent to which the core covers the internal surface of the cable.

Figure 2 is in sharp contrast to Figure 1. In the latter the relatively large R_c (2.5 μΩ [12]) allowed R_{eff} to increase gradually with increasing W. On the other hand with the Nb_3Sn cables the extremely small R_c (0.26 μΩ) forced R_{eff} to remain low as long as some crossing contacts remained uncovered. For the same reason, when W < 100% irregularities in core placement can produce a large scatter in R_{eff}.

V. Modelling of the Effective ICR in Cored Rutherford Cables

The above effects of core-width variation are revealed in Fig. 1 (a single NbTi cable design) and Fig. 2 (displayed for the first time for an assortment of Nb_3Sn cables). In order to further explore these core properties as they might apply to a QXF-type cable a coupling power, P_{coup}, versus W is calculated using the fortran program CUDI© [28]. Inserted into the program are: the "standard" R_a = 0.2 μΩ multiplied by N (to agree with the modified definition of R_a in CUDI©), the strand/strand R_c = 0.26 μΩ, and the core-moderated R_c = 1000 μΩ. Equations (1) and (2), arising from the Sytnikov expressions for coupling energy (J/cycle/m^3), can also be recast in terms of coupling power, P_{coup}, (W/m^3) as in (3).

$$P_{coup} = \left(\frac{1}{3}\right)\left(\frac{w}{t}\right)L_p\left(\frac{N^2}{20}\right)\left[\frac{1}{R_{eff}}\right]\left(\frac{dB}{dt}\right)^2 \qquad (3)$$

TABLE I. ICR OF THIN-SS-CORED Nb_3Sn RUTHERFORD CABLES

ICR (μΩ)	Cover, W	Ref.	Comments
0.33	41%	[19][25]	Shifted to one side of centerline and curled
0.37	32%	[19][25]	Well centered core
0.9	58%	[28]	Off-center, leaving uncovered 1.5 strands on one side & 5.5 on the other
1.10	76%	[26]	High compaction
1.15	76%	[26]	Standard compaction
1.46	76%	[26]	Low compaction
7.90	77%	[19][25]	Off-center but covering centerline
15.3	92%	[13]	Calorimetric measurement
33	92%	[17]	Calorimetric measurement
64	91%	[20]	Calorimetric measurement
78	92%	[17]	1T applied field
164	91%	[20]	Magnetic measurement
172	89%	[20]	Magnetic measurement
172	91%	[24]	Magnetic measurement
246	89%	[20]	Calorimetric measurement
246	91%	[24]	Calorimetric measurement

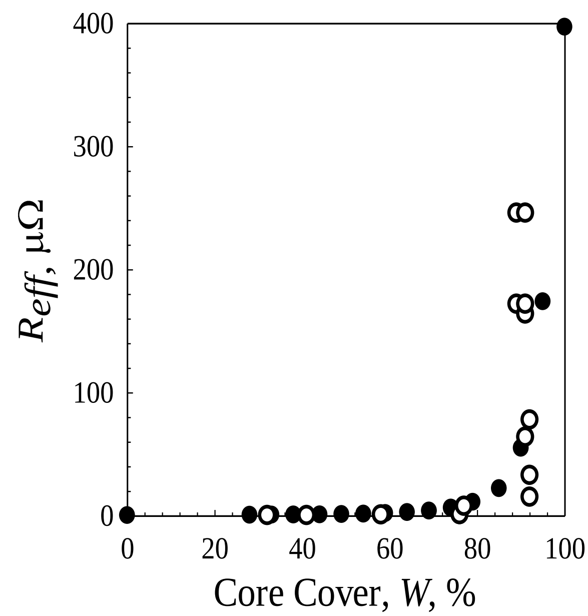

Fig. 2. R_{eff} versus W for SS-cored Nb_3Sn Rutherford cables. Experimental results for an assortment of cables (o); expected QXF-cable results based on CUDI© (●).

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Once appropriate volume normalization has taken place and the cable parameters inserted, the use of (3) enables a direct conversion of the power calculated by CUDI© to an R_{eff}. which in the case of the QXF cable is simply R_{eff} = 1.319/$P_{coup(\mathrm{CUDI})}$ μΩ. The calculations return R_{eff} = 652 μΩ for a fully insulating core, compared to an estimate using (1) giving $(N^3/20)0.2 = 640$ μΩ, and is consistent with the picture of R_{eff} as a parallel combination of R_c and $(N^3/20)R_a$. The CUDI©-based $R_{eff}(W)$ QXF results are displayed along with those for the assorted research Nb_3Sn cables in Figure 2.

VI. Discussion

Our measurements of a series of un-HT, stabrite-coated NbTi LHC-inner cables with stainless-steel (SS, insulating) cores showed $R_{eff}(W)$ decreasing smoothly from about 136 μΩ as W decreased from 100% [11][12]. On the other hand, our measurements of an assortment of SS-cored research cables wound by LBNL and FNAL (see Table I) showed R_{eff} plummeting abruptly and remaining low over most of the range. This difference in cable properties is due to the controlling influence of R_c (2.5 μΩ for the stabrite/NbTi and 0.26 μΩ for the Nb_3Sn) as more and more crossing strands become exposed. The experimental behavior was seen to agree with modelling-generated $R_{eff}(W)$s calculated by the program CUDI© using the basic parameters of the QXF cable (including R_a = 0.2 μΩ, R_c = 0.26 μΩ, R_c(across core) = 1000 μΩ). Further application of CUDI© demonstrated: (i) That R_{eff} dropped even more suddenly when the SS core, instead of being centered, was offset to one edge of the cable; Figure 3 shows R_{eff} decreasing on average by about 2½ times (e.g. at W = 90% from 55 μΩ down to 21 μΩ) following offset of the core. (ii) That R_{eff} decreased more gradually in cables with higher R_cs, Figure 4. Finally, based on the above, we conclude that a suitable R_{eff} for a Nb_3Sn quadrupole cable can be achieved by inserting, not a narrow SS core, but a suitably resistive (e.g. Cr-plated Cu [29] or SS) full-width one, the R_{eff} value of which, based on [29], can be estimated and is for comparison shown in Figure 4 (as an arrow indicating its R_{eff}).

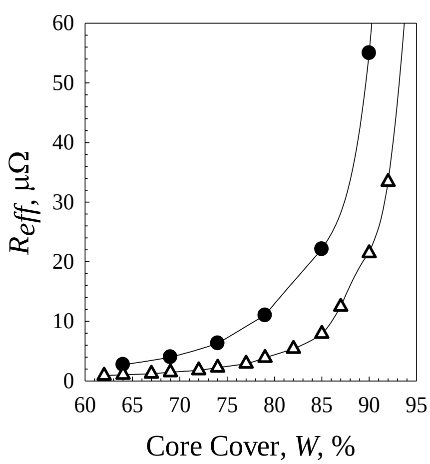

Fig. 3. Expected QXF-cable results (R_c=0.26 μΩ) based on CUDI© for centered insulating cores (●) and cores offset to one edge of the cable (Δ).

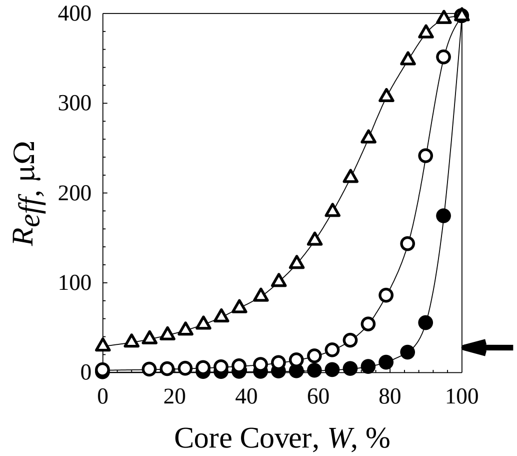

Fig. 4. Expected QXF-cable results based on CUDI© for centered insulating cores and R_c values of 0.26 (●), 2.5 (o), and 30 μΩ (Δ).

VII. Summary

The coupling magnetization of a Rutherford cable is inversely proportional to an effective interstrand contact resistance, R_{eff}, defined as $R_{eff} = [1/R_c + 20/N^3R_a]^{-1}$. In uncored cables R_{eff} is primarily controlled by R_c. The LHC magnet's uncored NbTi cables, wound with specially heat treated stabrite-coated strands, evidently have acceptable R_cs. It has been reported that the current ramping of LHC magnets produces field errors: (i) in dipoles of about 1 unit of b_1 and less than 0.1 units of c_n, consistent with R_c well above 50 μΩ, (ii) in quadrupoles of about 2 units of b_1 and less than 0.2 units of c_n, consistent with R_c between 100 and 150 μΩ. Evidently such R_cs have contributed to the successful operation of the LHC dipoles and quadrupoles to date and hence could be thought of as new target values when designing the Nb_3Sn cables for the LHC upgrades. But with measured R_cs of typically 0.3 μΩ bare Nb_3Sn cables are unsuitable; the cables need to be furnished with some kind of core to separate the crossing strands. In cables with insulating cores R_{eff} (now a function of both R_c and R_a) increases continuously with W (% core cover), with R_a eventually taking over as the controlling ICR. In seeking an optimal core width a large assortment of research cables were wound and measured over the years. The results, assembled and compared here for the first time, show $R_{eff}(W)$ reaching acceptable values only when W approached ~90% beyond which it increased very steeply. These experimental values were compared to modelling results using the program CUDI© choosing as our model cable a variable-width-core version of QXF. Further application of the program demonstrated that core positioning was important, R_{eff} decreasing by about 2½ times as the cores shifted from the center to one edge of the cable. As a result it is predicted that irregularities in core placement could produce a large scatter in R_{eff}. The sensitivity of R_{eff} to core width and position in the optimal large-W range leads to the suggested inclusion of a core, not of SS (which has a stable, insulating oxide surface layer), but of a resistive composite such as Cr-plated SS or Cr-plated Cu.

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